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PREDICTION OF FLUIDIZATION BEHAVIOUR AND A QUASI-STATIONARY APPROACH TO DRYING KINETICS OF IRREGULAR PARTICULATE FOOD MATERIALS

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ABSTRACT. Changes in fluidization behaviour behaviour was characterised for parallelepiped particles with three aspect ratios, 1:1, 2:1 and 3:1 and spherical particles. All drying experiments were conducted at 50^0C and 15 % RH using a heat pump dehumidifier system. Fluidization experiments were undertaken for the bed heights of 100, 80, 60 and 40 mm and at 10 moisture content levels. Due to irregularities in shape minimum fluidisation velocity of parallelepiped particulates (potato) could not fitted to any empirical model. Also a generalized equation was used to predict minimum fluidization velocity. The modified quasi-stationary method (MQSM) has been proposed to describe drying kinetics of parallelepiped particulates at 30^o C, 40^o C and 50^o C that dry mostly in the falling rate period in a batch type fluid bed dryer.

Keywords: Fluidization, Generalised model, Quasi-stationary approach, irregular particulate

INTRODUCTION

The minimum fluidisation velocity of a material is the superficial velocity at which material bed starts to fluidise The Ergun equation (Ergun, 1952) is the widely accepted model to determine *minimum fluidization velocity* of a fluid to fluidize the particle (Kunii and Levenspiel, 1969; Zenz and Harbor, 1971; Michelis and Calvelo, 1994).The Ergun equation (Equation 1) is used to calculate minimum fluidization velocity of baker's yeast (Egerer et al., 1985), peas (Rios et al., 1984) and diced potato and potato strips (Vazquez and Calvelo, 1980; Vazquez and Calvelo, 1983). An equation similar to Ergun is valid for peas (Michelis and Calvelo, 1994). The values for velocity obtained by the Ergun equation are mostly reliable for spherical and relatively small particles. Most agro-food particulates however comprise of various shapes and sizes, and consist of larger particles. Therefore, the minimum fluidization values obtained from Ergun equation do not conform to the experimental values (Mclain and McKay, 1980, 1981a, 1981b; McKay et al., 1987)

$$(1-\varepsilon_{mf})(\rho_s-\rho_f)\,g = 150\frac{(1-\varepsilon_{mf})^2}{\varepsilon_{mf}{}^3}\frac{\mu u_{mf}}{(\phi d_p)^2} + 1.75\frac{(1-\varepsilon_{mf})}{\varepsilon_{mf}{}^3}\frac{\rho_f u_{mf}{}^2}{\phi d_p} \qquad (1)$$

where ε_{mf} – bed porosity at minimum fluidization velocity, ρ_s – particle density (kg/m^3), ρ_f – fluid density (kg/m^3), μ - viscosity (N s/m^2), u_{mf} – minimum fluidization velocity (m/s), d_p – particle equivalent diameter (m), ϕ - sphericity

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The Ergun equation consists of *viscous* and *kinetic energy* terms. In the case of larger particles at higher Reynolds numbers (Re > 1000) the fluidization behaviour is mainly governed by the kinetic energy term in the Ergun equation. Hence the Ergun equation can be simplified for (Kunii and Levenspiel, 1969) a wide variety of systems and a generalized equation can be applied to predict minimum fludisation velocity for larger particles when Reynolds number > 1000 using some modification.

$$u_{mf}^{\ 2} = \frac{\phi d_p}{1.75} \frac{(\rho_s - \rho_f)}{\rho_f} g \varepsilon_{mf}^{\ 3} \tag{2}$$

where, ε_{mf} – bed porosity at minimum fluidization velocity, ρ_s – particle density (kg/m^3), ρ_f – fluid density (kg/m^3), u_{mf} – minimum fluidization velocity (m/s), d_p – particle equivalent diameter (m), ϕ - sphericity, g - acceleration due to gravity (m/s^2)

For wide variety of systems it was found that value $\frac{1}{\phi\ \varepsilon_{mf}^{\ 3}} \cong 14$ (Wen and Yu, 1966) and a generalized equation can be applied to predict u_{mf} for larger particles when Re > 1000.

$$u_{mf}^{\ 2} = \frac{d_p(\rho_s - \rho_f)}{24.5\rho_f} g \tag{3}$$

where, ρ_s – particle density (kg/m^3), ρ_f – fluid density (kg/m^3), u_{mf} – minimum fluidization velocity (m/s), d_p – particle equivalent diameter (m), Re – Reynolds number

There is a continuous change in physical properties of the particulates during drying, which also changes the fluidization behaviour of the particles. It is very important to understand these changes, so that the air-flow during drying can be controlled to achieve an optimum fluidization.

Some limitations of the empirical models derived to describe drying characteristics could be eliminated by using a semi-empirical approach. Such a method is the modified quasi-stationary method (Efremov, 1999). This method has been proposed to describe drying kinetics of parallelepiped particulates at three drying temperatures where particles dry mostly in the falling rate period in a batch type fluid bed dryer. The model is based on mass conduction of solid materials in bulk, given in terms of effective moisture diffusivity, resulting in the following semi-theoretical equation for drying kinetics;

$$MR = \frac{m - m_e}{m_i - m_e} = \frac{1}{1 + \left(\frac{t}{\sigma}\right)^p} \tag{4}$$

Where, MR – dimensionless moisture, m – moisture at given time (kg/kg db), m_e – equilibrium moisture (kg/kg db), m_i – initial moisture content, t-drying time (h), σ – characteristic time (h) and p – dimensionless parameter

The objective of this study is to understand changes in minimum fluidization velocity for a parallelepiped food material during drying and relate this to moisture content by a suitable model, and compare the experimental minimum fluidization velocity with the generalized model predictions. Also a modified quasi-stationary method (MQSM) has been proposed to describe drying kinetics of parallelepiped particulates at 30^{o}C, 40^{o}C, and 50^o C in a batch type fluid bed dryer.

MATERIAL AND METHODS

Material preparation

Potato *Solanum tuberosum* of the variety Sebago was purchased from the same supplier in 50 kg bags. Parallelepipeds were made in a Dicing Machine (Hobart, Australia), by incorporating a cutter which makes 6.5mm X 6.5mm square cross-section. According to the required aspect ratios of 3:1, 2:1 and 1:1, the particles were cut carefully to lengths of 19.5, 13 and 6.5 mm respectively using a cutting blade. Immediately after cutting, all the samples were immersed in a sodium metabisulphite solution (0.1 % w/w) for 15 minutes to prevent browning during drying. The samples were drained on a mesh tray. Then samples were placed in a plastic bag and kept it in a cold room for 24 hours at 4^{o} C in order to produce uniform moisture distribution within the sample.

Particle density determination. To determine the particle density, a known number of particles were weighed by an electronic balance (Sartorius), and the volume was measured by the difference in meniscus levels before and after immersion of particles in liquid paraffin in a measuring cylinder. The difference in meniscus levels was measured by a vernier caliper (accuracy 0.05mm). This value was used to calculate the equivalent diameter of the particle, which was used in the generalized equation (Equation 3).

Moisture content determination. Moisture content was determined by measuring the loss in weight of finely chopped samples held at 70^{0} C and 13.3 Kpa vacuum for 24 hours (AOAC, 1995).

Experimental method for fluidisation experiment

First, fluidisation characteristics of the un-dried samples were measured in the fluidizing column with the prepared samples. After that samples were dried on a fixed bed in a heat pump dehumidifier system and samples were withdrawn at nine pre-determined time intervals during drying and used for measurement of fluidisation characteristics at different moisture contents. Fluidisation characteristics measured were minimum fluidisation velocity at four bed heights of 100, 80, 60, and 40 mm in a fluidized bed column (Figure 1).

Figure 1. Fluidisation column connected to the heat pump dryer

Drying in a fixed bed. Samples for studying fluidisation behaviour were dried in a heat pump dehumidifier system (Baleden Pty Ltd, Brisbane, Australia) in Food Science and Technology, School of Land and Food Sciences, University of Queensland, Gatton, Australia (Figure 1). The drying was undertaken at an air temperature of 50^{o} C (which is a common drying temperature) and relative humidity of 15 %. Before materials were loaded in the dryer, the dryer was run for 2 hours to achieve steady state conditions. Materials were placed into the drying system on mesh trays as thin layers, and stacked vertically to achieve maximum exposure to the air-flow. Samples were removed at nine pre-determined time intervals. They were placed into a sealed container and immediately used for fluidizing experiments. For moisture determination, samples were stored immediately in a pre-dried sample bottle.

Determination of minimum fluidisation velocity All fluidisation trials were conducted in a batch type flexi-glass fluidizing column of 185 mm inside diameter and length 1 m (Figure 1). The hot air was taken from a heat pump dehumidifier system (Intertherm P/L, Brisbane, Australia) coupled to the fluidizing column by flexible ducts. Bed height was measured from a scale attached to the column. The change of bed pressure drop was measured while increasing the velocity through the bed for each height. In order to determine the optimum bed height for improved fluidisation bed heights of 100, 80, 60 and 40 mm were used. Measurements of pressure drop for each bed height took less than 3 min.

Visual observation of the bed at an instance of fluidization after bed expansion was the criteria considered to categorise minimum fluidization. Also this value was compared with graphical variation of the pressure drop of the bed with velocity. Both observed and graphical values were identical.

Drying in a fluidised bed One batch stored in the cold room was taken for fluidised bed drying experimentation. Fluidised bed dryer was connected to the heat pump dehumidifier system (Figure 1). The drying conditions of 30^0 C, 40^0 C and 50^0 C were set by the temperature controller in the heat pump dehumidifier system, and the drying set up was run for 2 hours to achieve steady state conditions of drying before material introduction. Initial bed height of 150 mm was used. The hot air velocity passing through the material bed was kept at a constant value of 2.2 m/s for all drying experiments. This velocity was selected, because it was within the limit of fluidisation and terminal velocity of the material concerned and within the capability of the fan. The air-flow entering the dryer was controlled by flow control valves. Samples were collected from the dryer at 30 minutes intervals through the sample outlet. Each time they were collected in a sealable container and immediately used for moisture determination and volume measurements.

ANALYSIS OF EXPERIMENTAL DATA AND MODELLING PROCEDURE

Fluidisation data were analysed for the analysis of variance (ANOVA) to evaluate differences, and, linear and non-linear regression to obtain suitable models. The coefficients of Equation 4 were estimated using Matlab (2008) Curve Fitting Tool Box on a personal computer. Model validity was tested using measures of coefficient of determination (R^2) and mean absolute error percentage (MAE%). Mean absolute error percentage (MAE%) (Equation 5) was calculated according to the methods given by Mayer and Butler (1993) for different L:D ratios and are given in Table 1.

$$\mathrm{MAE\%} = 100\left[\Sigma\,(\left|y_i - \hat{y}_i\right| / \left|\hat{y}_i\right|)\right] / n \qquad (5)$$

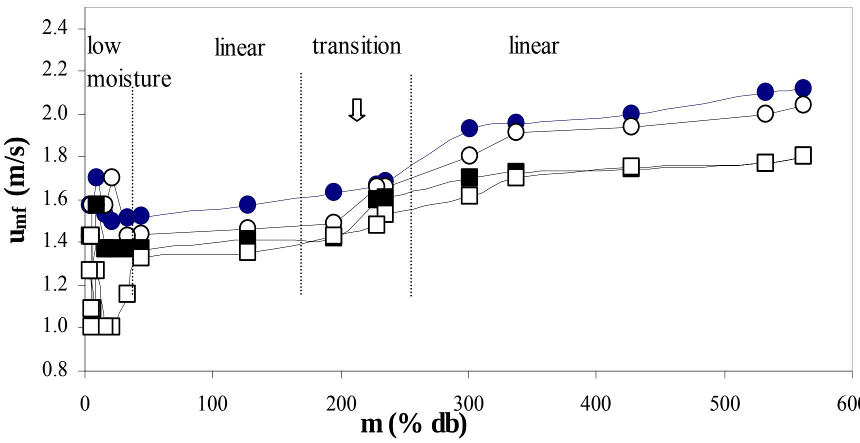
RESULTS AND DISCUSSION

Fluidisation behaviour

For aspect ratio 1:1, minimum fluidization occurred together with slugging and channeling at the moisture 560 % db for all bed heights. Reduction in minimum fluidization velocity was fairly linear down to 300 % db moisture. Between moisture contents values 220~260 % db, there existed a sudden change of minimum fluidization value for all bed heights (which described as the transition region in Figure 3). The magnitude of this change in minimum fluidization velocity decreased as bed height decreased. At low moisture values irregular behaviour in fluidization velocity was observed due to uneven shrinkage and interlocking of particles. Figure 2 shows fluidization behaviour of potato with aspect ratio 1:1, which shows some what regular fluidization behaviour.

In the case of aspect ratio 2:1 (graph not shown), when moisture content of particles was initially 570 % db, fluidization did not start until 310 % db moisture for the bed height of 100 mm, and at 340 % db moisture for the remainder of the bed heights. Sudden changes in minimum fluidization velocity were observed between moisture values of 140 % and 160 % db, a very narrow moisture range. This may be due to change in bed porosity. Below 140 % db moisture content minimum fluidization velocity was reduced showing irregular behaviour below 40 % db moisture, similar effect as 1:1.

For aspect ratio 3:1 at 100 mm bed height particles tend to fluidise after they have been dried too a moisture content of 300 % db from initial moisture of 540 %. In all other bed heights, fluidization started when moisture content was less than 326 % db. Suden change in minimum fluidization velocity was observed in the middle ranges of moisture content (60% - 70 % db). As moisture reduced during drying also resulted in increasing sphericity value (which was not measured) could have been contributed to better fluidization.



• 100 mm o 80 mm ■ 60 mm □ 40 mm

Figure 2. Fluidisation behaviour of potato aspect ratio = 1:1

<u>*Modelling of minimum fluidisation velocity with change in moisture content*</u>. Fluidisation behaviour of potato particles could not be modelled due to the irregular trend of change of minimum fluidisation velocity with moisture content for all aspect ratios. The change of minimum fluidization velocity with moisture reduction was less for lower bed heights. The change of minimum fluidization velocity with the moisture reduction was less for lower bed heights. For aspect ratio of 1:1 u_{mf} ($m \simeq 0$) increased from 1.1 m/s to 1.6 m/s when bed height increased from 40 mm to 100 mm. For aspect ratio of 2:1, u_{mf} ($m \simeq 0$) increased with increased bed heights and changed from 1.3 m/s to 1.7 m/s for the bed heights of 40 mm to 100 mm respectively. This change for aspect ratio 3: was in the range 1.8 m/s to 2.1 m/s.

<u>*Minimum fluidisation velocity calculation based on the generalized equation.*</u> The Generalized model was used to calculate the predicted values of minimum fluidisation velocity. For all three aspect ratios, this generalized model value was compared with the experimental value. The mean absolute error percentage value is more than 10% for the aspect ratio 3:1, for the bed heights of 100, 80 and 60 mm (Table 1).

Table 1

Mean absolute error percentage (MAE %) of observed and predicted values

Aspect ratio	MAE%			
	100mm	80mm	60mm	40mm
1:1	8.83	4.09	2.75	2.03
2:1	7.55	6.26	1.03	1.02
3:1	13.46	12.98	10.80	3.68

The generalized model predicted minimum fluidization velocity changes from 1.30 m/s (5 % db moisture) to 1.68 m/s (562 % db moisture) for the aspect ratio 1:1. The predicted minimum fluidization velocity for the aspect ratio 2:1 varied from 1.45 m/s (4.3 % db moisture) to 1.76 m/s (338 % db moisture). The variation in predicted minimum fluidization velocity for the aspect ratio 3:1 was 1.58 m/s (4.7 % db moisture) to 2.12 m/s (326 % db moisture). (Predicted and observed plots are not shown).

Quasi-stationary approach to drying kinetics

Table 2 shows the value p (Index of Hydrodynamic Intensity) in equation 4, which is a representation of hydrodynamic condition of the bed during drying experimentation for different aspect ratios.

Table 2

Index of hydrodynamic intensity (p) for different aspect ratios

L:D Ratio	p
1:1	1.81
2:1	1.69
3:1	1.67

From the values given in Table 2 it was observed that Hydrodynamic intensity (p) of the fluidized bed is vary with the size. The slight variations observed among sizes, may be attributed to channeling and slugging behaviour of the particles at higher initial moisture contents. Also it can be both material shape and aerodynamic of the bed dependent. Table 3 shows the characteristic times (σ) for different aspect ratios and drying conditions.

Table 3

Characteristic time for different aspect ratios at drying temperatures

	30^{o}C	40^{o}C	50^{o}C
1:1	0.9268	0.7814	0.5797

2:1	1.059	0.9392	0.7720
3:1	1.122	1.038	0.7920

Good agreement of experimental data with predicted values indicate that the parameters obtained for hydrodynamic intensity and characteristic time (For all the cases coefficient of determination R^2 was above 0.99). It was also observed that characteristic time was proportional to the drying air temperatures and decreased with increased temperature.

CONCLUSION

Fluidisation behaviour with moisture could not be modelled for parallelepiped (potato) particles due to its irregular nature. But generalised equation predicts the minimum fluidisation with a reasonable accuracy for the particles. If sphericity changes during drying is measured an accurate predictions of minimum fluidisation velocity could be obtained using Ergun Equation. Onset of fluidisation of particles depended on bed height, sphericity and moisture content. Good fluidisation was observed only at low moisture levels. The magnitude of the minimum fluidisation velocity decreased with the decreased bed height and with decreased moisture content. The modified quasi stationary could be used to describe drying kinetics of the fluid bed drying accurately and characteristic drying time decreased with increased drying temperature.

NOMENCLATURE

d	equivalent diameter	(m)
D	diameter	(m)
g	acceleration due to gravity	(m/s^2)
L	length	(m)
m	moisture content (dry basis)	(kg/kg db)
MR	dimensionless moisture	
p	hydrodynamic intensity	
Re	Reynolds number	
t	drying time	(h)
u	velocity	(m/s)
y	value	
σ	characteristic time	(h)
ϕ	sphericity	
ε	porosity	
ρ	density	(kg/m^3)
μ	viscosity	($N\ s/m^2$)

Superscripts

$\wedge$	predicted value

Subscripts

e	equilibrium
f	fluid
i	integer
mf	minimum fluidization
n	no of observations
o	initial
p	particle

s solid

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